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TECHNICAL NOTE

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AN EXPERIMENTAL INVESTIGATION OF THE DAMPING OF LIQUID OSCILLATIONS IN CYLINDRICAL TANKS WITH VARIOUS BAFFLES

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

WASHINGTON May 1961

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SUMMARY

An experimental investigation was conducted to determine the effects of baffle configuration, width, and location on the damping characteristics and frequency of the fundamental antisymmetric mode of liquid oscillations in right-circular cylindrical tanks. Baffle configurations studied include fixed rings, rings with radial clearance, cruciforms, and conic sections. For the conic-section baffles, upright, inverted, and perforated configurations were examined. Some results of studies of effects of amplitude of the liquid oscillations and kinematic viscosity on the damping are also presented. The damping results obtained in the investigation are in agreement with those predicted by available semiempirical analytical methods.

INTRODUCTION

In missiles or in space-flight boosters in which liquid-fueled propulsion systems are used, the response of the vehicle to motions of the contained liquid may greatly affect the stability and control of the vehicle. In particular, if the liquid masses are excited at a frequency near that of a lower liquid mode, the amplitude of the liquid oscillations, and hence the resultant forces and moments, may be of such magnitude as to induce flight instabilities or structural failures. The severity of this problem is cited in reference 1 where the failure of large vehicles has been attributed to propellant sloshing.

In an attempt to avoid such failures, tanks are currently being fitted with various baffle configurations which damp the liquid motions and thus reduce the magnitudes of the forces and moments on the vehicle. The effects of baffle configuration, width, thickness, flexibilty, and location on the damping and frequency of the fundamental antisymmetric mode of liquid oscillations in cylindrical tanks are therefore of particular importance. However, analytical means for predicting damping are limited to special cases (ref. 2) because of the complexity of the boundary conditions (ref. 3); also analytical expressions for the natural frequency are limited to tanks without baffles (ref. 4).

In order to obtain further information on this subject, an experimental investigation of the damping characteristics and natural frequency of the fundamental antisymmetric mode of water in a 12-inch-diameter tank were examined. Prime variables considered were: baffle width, configuration, location, and orientation; amplitude of oscillation; and kinematic viscosity of the liquid. In order to determine the applicability of the results to tanks of larger size, an investigation was conducted using a ring baffle in a 30-inch-diameter tank. The results of this investigation are reported herein.

SYMBOLS

a	fractional part of cross-sectional area of tank that is blocked by baffle
c	radial clearance between tank wall and baffle
d	distance of baffle below free surface
h	liquid depth
M_n	amplitude of nth moment
M_o	amplitude of initial moment
n	number of cycles
R	cylinder radius
w	width of baffle annulus projected on liquid surface
δ	damping factor, $\frac{1}{n} \log_e \frac{M_o}{M_n}$
ζ	wave amplitude
f	natural frequency of liquid oscillation, cps

APPARATUS

Tanks

The investigation of the damping of liquid oscillations was conducted with two right-circular cylindrical tanks of 12- and 30-inch inside diameters as shown in figure 1. The smaller tank shown in figure 1(a) was constructed of 1/8-inch Plexiglas with the base secured to a metal platform. The metal platform was then connected to an outer support ring by torsion bars.

The 30-inch-diameter tank shown in figure 1(b) was fabricated from 0.016-inch aluminum. A 1/2-inch aluminum plate was used as the base for this tank.

Baffles

The types and dimensions of the six baffle configurations studied in the 12-inch-diameter tank are shown in figure 2. The baffles used in this tank were constructed of 1/8-inch Plexiglas except the conic-section baffles, in which 1/16-inch Plexiglas was used. The base angle of the conic-section baffles was maintained at 45°. The perforated conic section (fig. 2(e)) had a 50-percent reduction in area obtained by using 1/8-inch-diameter perforations. In the 30-inch-diameter tank, a 1/4-inch-thick Plexiglas fixed ring baffle was used with a w/R ratio of 0.076. In all cases, the rectangular edges of the baffle material were retained.

Instrumentation

The moments resulting from liquid oscillations in the 12-inch-diameter tank were sensed by strain gages mounted on the torsion bars between the base platform and the support ring as shown in figure 1(a). The liquid oscillations in the 30-inch-diameter tank were measured by using a load cell, shown in figure 1(b), as one of the three platform supports. The output signals from the gages and load cell were amplified and fed into a Dampometer to measure the damping and frequency of the liquid motion.

PROCEDURE

The liquid was excited in the fundamental antisymmetric mode of oscillation by means of a paddle. When a sufficient liquid amplitude was obtained, the excitation was removed. The rate of decay of the moment resulting from the liquid oscillations was then measured between two preselected values of the moment. The decay of the oscillation specified by the damping factor δ is defined as

$$\delta = \frac{1}{n} \log_e \frac{M_o}{M_n} \qquad (1)$$

where n is the number of cycles over which the decay was measured, M_o is the amplitude of a selected initial moment, and M_n is the amplitude of a selected terminal moment after n cycles. Since the damping is a nonlinear function of the liquid amplitude, the experimental data depend upon the magnitude of the initial moment and the ratio M_o/M_n, both of which could be selected and maintained for a given test.

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The six baffle configurations were compared by measuring the variation in damping factor with baffle location in the 12-inch tanks. For this study the value of M_o was slightly below the maximum moment for which the fundamental mode could be defined for all the baffle test conditions. The moment M_o would correspond approximately to the moment produced by a 1-inch-amplitude wave in the 12-inch-diameter tank without baffles with a water depth of 12 inches. For the comparison the value for M_n was $0.3M_o$ so that several oscillations were used in obtaining the damping value. The damping provided by each baffle was obtained for baffle locations ranging from the liquid surface to a location where the damping became relatively small except in the case of the cruciform baffle where the damping was not dependent on the location of the liquid surface.

The variation of damping with amplitude was studied with the use of the $\frac{w}{R} = 0.076$ ring baffle located at $\frac{d}{R} = 0.333$ in the 12-inch-diameter tank. For this study a value of M_n equal to $0.7M_o$ was used to decrease the increment selected in measuring the decay rate. The amplitude of the oscillation could therefore be specified approximately as that value corresponding to the initial moment M_o. This amplitude above the equilibrium surface was read visually with the aid of a scale.

A limited study was made to determine the effects of tank diameter. A ring baffle of $\frac{w}{R} = 0.076$ was used in a 30-inch-diameter tank and the damping factor was determined at various locations of the baffle below the surface. These values were compared with those obtained in the 12-inch-diameter tank. For this comparison a value of M_n equal to $0.7M_o$ was again selected to facilitate the measurement of amplitude.

Some damping factors were measured by using the $\frac{w}{R} = 0.076$ ring baffle located at $\frac{d}{R} = 0.333$ to examine the effect of kinematic viscosity on the damping. Variations in the liquid viscosity were obtained by heating and cooling water in the 30-inch-diameter tank.

A preliminary investigation utilizing the same procedures that were used in the baffle-configuration comparisons was made to assess the effects of the thickness and flexibility of the baffles.

DISCUSSION OF RESULTS

The consistency of the experimental data will be considered before discussing in detail the damping afforded by the various baffle configurations. The damping factor will then be discussed for the various baffles, and factors involved in extrapolating these results to tank sizes of practical interest will be considered. The agreement between these results and those predicted by semiempirical analytical methods will be examined. Finally, the effect of liquid amplitude on the damping factor and the effect of baffles on the frequency of the fundamental mode of oscillation will be discussed.

General

Because of the turbulent nature of the liquid in the regions of higher damping, some scatter occurred in the data. The magnitude of this scatter is shown in figure 3, where each of the measured values of damping is shown as a function of baffle location for a typical baffle. The curve represents a fairing of the average values of the damping factor measured at each location of the baffle. The greatest scatter is shown to exist in the region of maximum damping; therefore, the accuracy of the curve in the region of this peak is somewhat less than that in the other regions. In the following results, all damping values presented represent the average of five or more measured values for the given condition.

Flat Ring Baffles

<u>Fixed</u>.- The damping provided by four fixed ring baffles (fig. 2(a)) is shown as a function of baffle location in figure 4. The measured values of damping are in terms of the dimensionless damping factor δ, and the location is specified by the ratio d/R where d is the distance from the undisturbed surface to the baffle and R is the tank radius. Curves are faired through the data to differentiate the ring sizes which are given by w/R where w is the width of the ring. The values of damping for the largest ring tested were not obtained in the range of maximum damping due to the difficulty involved in exciting

the mode. The regions of maximum damping are shown by dashed curves when an uncertainty existed in defining the exact location of maximum damping.

The trends of the faired curves for all fixed rings are similar. The value of damping present when the baffle is flush with the surface is reduced considerably since the baffle is in contact with the fluid for only a portion of the period. The damping increases as the distance between the equilibrium surface and the baffle is increased, reaching a maximum at the minimum depth below the surface at which the ring does not break the surface during the oscillation. As the distance between the baffle and the equilibrium surface is further increased, the damping decreases rapidly approaching the value of damping present when no baffle is incorporated.

With radial clearance.- The variations in damping factor with baffle location are presented in figure 5 for five ring baffles of various widths w and radial clearances c (fig. 2(b)). Measured values of δ are given as a function of baffle location d/R for each configuration. In the range considered, the curve indicates that the damping factor decreases as the radial clearance is increased for a given ring width, while the damping factor increases with ring width for a given radial clearance. This figure is again indicative of the fact that a range of maximum damping exists at values of d/R just below the equilibrium surface and that a rapid decrease in damping occurs as the baffle depth is further increased.

Conic-Section Baffles

Upright.- The results obtained for four upright conic-section baffles (fig. 2(c)) having projected areas on the equilibrium surface approximately equal to the areas of the fixed ring baffles are shown in figure 6. The location is specified by d/R where d is the distance between the top edge of the baffle and the equilibrium surface and is equal to zero when the baffle is just submerged.

The trends and maximum values of damping shown in this figure are very similar to those of the fixed rings. Although the damping provided by the conic sections is slightly higher than that for the fixed rings, the surface area of a conic-section baffle having the same value of w/R as that for the fixed ring is considerably higher.

Inverted.- The variation of damping with baffle location for an inverted-conic-section baffle (fig. 2(d)) is shown in figure 7. Again the trend of the curve is similar to that of the flat rings and conic sections; however, the maximum value of damping occurs when the baffle is approximately half submerged in the liquid. This shift in location of the baffle for maximum damping is apparently due to the almost complete restriction of the fluid motion in the region between the baffle and the tank wall when the baffle is in this location. The data show that the effectiveness of the baffle is less than that of either the ring or upright conic section of comparable size.

Perforated.- The results obtained from two perforated conic sections (fig. 2(e)) having a 50-percent reduction in blockage area are shown in figure 8. These results are limited since the effects of hole size and percentage reduction in area were not studied. It is of interest, however, to compare the trend and values of the damping factor with those of the solid conic sections. The sharp peaks observed for the solid-conic-section baffles are reduced for the perforated baffles. The damping factor in the range of maximum effectiveness has been reduced by more than a factor of 2 when compared with a comparable solid conic section.

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Cruciform Baffles

The damping provided by cruciform baffles (fig. 2(f)) was measured for two orientations of the baffle with respect to the motion of the liquid in the fundamental mode. For the 90° position where two sections are located on the node line and two sections are 90° from the node line $\delta = 0.072$ was measured for the $\frac{w}{R} = 0.169$ baffle and $\delta = 0.156$ was measured for the $\frac{w}{R} = 0.337$ baffle. In the 45° position the damping factors were $\delta = 0.070$ and $\delta = 0.142$ for the $\frac{w}{R} = 0.169$ and $\frac{w}{R} = 0.337$ baffles, respectively.

Summary Comparison

The results shown in figures 4 to 8 plus the results obtained from two cruciform baffles are summarized in figure 9. The mean value of damping obtained in the location of maximum effectiveness is shown for each baffle. This value was obtained by dividing the area under the curve between $0.084d/R$ above and $0.084d/R$ below the maximum damping, by $0.168d/R$. For cases where values for δ were not available for $0.084d/R$ above the peak, the curves were extrapolated and the resulting areas were measured. These values are dependent upon the limits chosen, of course, and are presented as a means of comparison only. For example, if the range examined had been larger than $\frac{d}{R} = 0.168$, the mean value would have been lower in all cases except for that of the cruciform baffles where the damping factor is independent of d/R. This method of comparison was chosen because of the uncertainty involved in defining the maximum value of damping afforded by each baffle. Values are not shown for the largest ring and conic-section baffles since data were not obtained for these cases in the region of maximum damping.

The cruciform baffles appear to provide lower damping than the other baffles of comparable size. The effect of orientation was small although there appears to be a slight advantage when the baffle is oriented 90° to the direction of the fluid motion.

Application

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In order to determine the range of application of the experimental results, tests to examine the effects of tank size, kinematic viscosity, and liquid amplitude on the damping were made and the agreement with an available method of predicting the damping was examined.

Effect of tank size.- The results obtained from the 12-inch-diameter tank in which a $\frac{w}{R} = 0.076$ fixed ring baffle was installed are compared with those of a geometrically similar 30-inch-diameter tank with a $\frac{w}{R} = 0.076$ fixed ring baffle in figure 10. Also shown in this figure are the calculated values of damping obtained from the following semi-empirical relationship developed by Miles and given in reference 5:

$$\delta = (2\pi)2.83e^{-4.60d/R}\, a^{3/2}(\zeta/R)^{1/2} \tag{2}$$

where ζ is the wave amplitude and a is the fractional part of the cross-sectional area of the tank that is blocked by the baffle, and a is given by the following expression:

$$a = \frac{R^2 - (R - w)^2}{R^2} \tag{3}$$

Limits of the output moment were such that the experimental value of damping was obtained by using $n = 1$ to $n = 5$ cycles of the oscillation. The amplitude of the oscillation corresponding to M_o which was necessary for the calculation of damping was measured during the determination of the decay rate. The range of application of the experimental results is indicated by the fact that the dimensionless data presented are independent of tank size for the 12- and 30-inch-diameter tanks and agree closely with the results calculated by use of equation (2).

<u>Effect of kinematic viscosity</u>.- The effect of kinematic viscosity on the damping was studied in the 30-inch-diameter tank fitted with a fixed ring baffle at a given location. The results of this study are shown in figure 11. The kinematic viscosity was varied by changing the temperature of the water between approximately 40° F to 140° F and, for the range considered, no apparent effect of viscosity was noted.

<u>Effect of amplitude</u>.- An investigation of the variation of damping with amplitude was conducted in the 12-inch-diameter tank fitted with the ring baffle, $\frac{w}{R} = 0.076$, located at $\frac{d}{R} = 0.333$ and the results are shown in figure 12. The measured values for fluid depths of 12 and 15 inches are compared with values calculated by using equation (2). In this study a divider baffle which extended down to the ring was used for most of the tests and this would tend to increase the value of the damping factor, as is indicated by most of the experimental data shown. However, data are also given for a test in which the divider baffle is removed. The measured values of damping are plotted as a function of the initial value of the amplitude of the liquid oscillation. A comparison of the measured data with the curve calculated by use of Miles equation from reference 5 shows that both the trends and magnitudes of the damping predicted by that equation agree closely with the results measured.

<u>Effect of baffle on natural frequency</u>.- The variation in the frequency of the fundamental mode of the liquid oscillations was measured simultaneously with the damping factor and is shown in figures 13 to 17. The maximum values of the frequency of the ring baffles and conic-section baffles were found when the baffle location was $\frac{d}{R} = 0$, which is probably due to the baffle effectively decreasing the diameter of the cylinder. The frequencies for the tanks with the radius reduced by the ring width were also calculated by using reference 4 and are shown in figure 13 to be generally somewhat lower than the measured values. For the ring baffle, as the baffle is lowered below the surface, the frequencies of the fluid motions continue to decrease from the value obtained when the ring is located at the surface until a minimum value is reached wherein the baffle depth corresponds to the value which produces maximum damping. As the baffle is further lowered, the frequency increases to the free-surface value. The decrease in frequency may be caused by a tendency of the baffle to restrict the motion of the liquid to that of an equivalent shallow tank of the same diameter. This effect decreases as the baffle moves to a greater depth until the frequency corresponds to the free-surface value.

<u>Effect of baffle thickness and flexibility</u>.- The preliminary results of baffle thickness were somewhat limited but for the amplitudes of the tests, the damping results measured for a baffle thickness as low as 0.008 inch did not differ substantially from those measured for

a baffle 1/8 inch thick. Additional preliminary studies have further shown that the flexibility of the baffle may be an important factor. These tests have indicated that the damping may increase with some increase in the flexibility of the baffle. In view of the relationship of baffle thickness and flexibility, additional research is necessary to isolate the effects of these and other parameters before definite conclusions can be drawn.

CONCLUSIONS

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An investigation has been conducted to determine the effects of various baffle configurations on the damping of the fundamental mode of oscillation of liquids contained in cylindrical tanks and the results are summarized as follows:

1. The location of the flat ring and conic-section baffles necessary for a substantial increase in damping is limited to a narrow range near the liquid surface.

2. For locations near the liquid surface, the damping factor increases with the size of the flat ring and of the conic-section baffles; however, for baffle locations well below the liquid surface, increases in baffle size do not result in substantial increases in damping.

3. For a ring baffle of a given width and location, the damping factor decreases as the radial clearance increases.

4. The damping factor for the inverted- and perforated-conic-section baffles is less than that for the upright-conic-section baffle of the same area.

5. Based on the total surface area of a baffle, the highest mean damping factor for the baffles tested appears to be afforded by the fixed ring baffle.

6. A comparison of the damping values measured for the fixed ring baffle with those calculated by the semiempirical method of Miles shows that this method is adequate for the prediction of the damping for this configuration when the baffle remains below the surface.

7. The frequency of the fundamental mode of oscillation varies with baffle location and is believed to be due to the baffle effectively changing the tank geometry.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., December 7, 1960.

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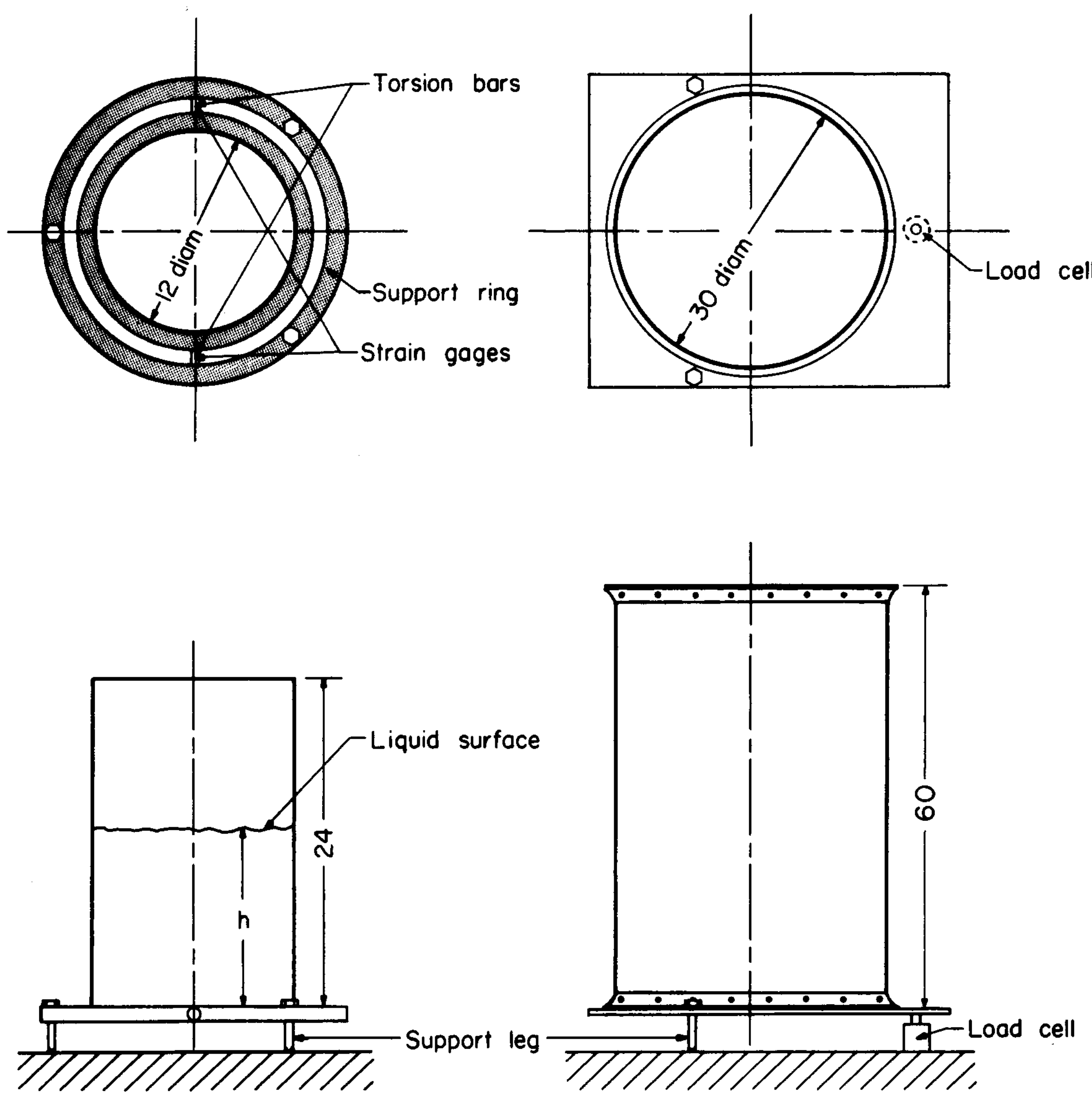

(a) 12-inch-diameter tank. (b) 30-inch-diameter tank.

Figure 1.- Tank configurations. All dimensions are in inches.

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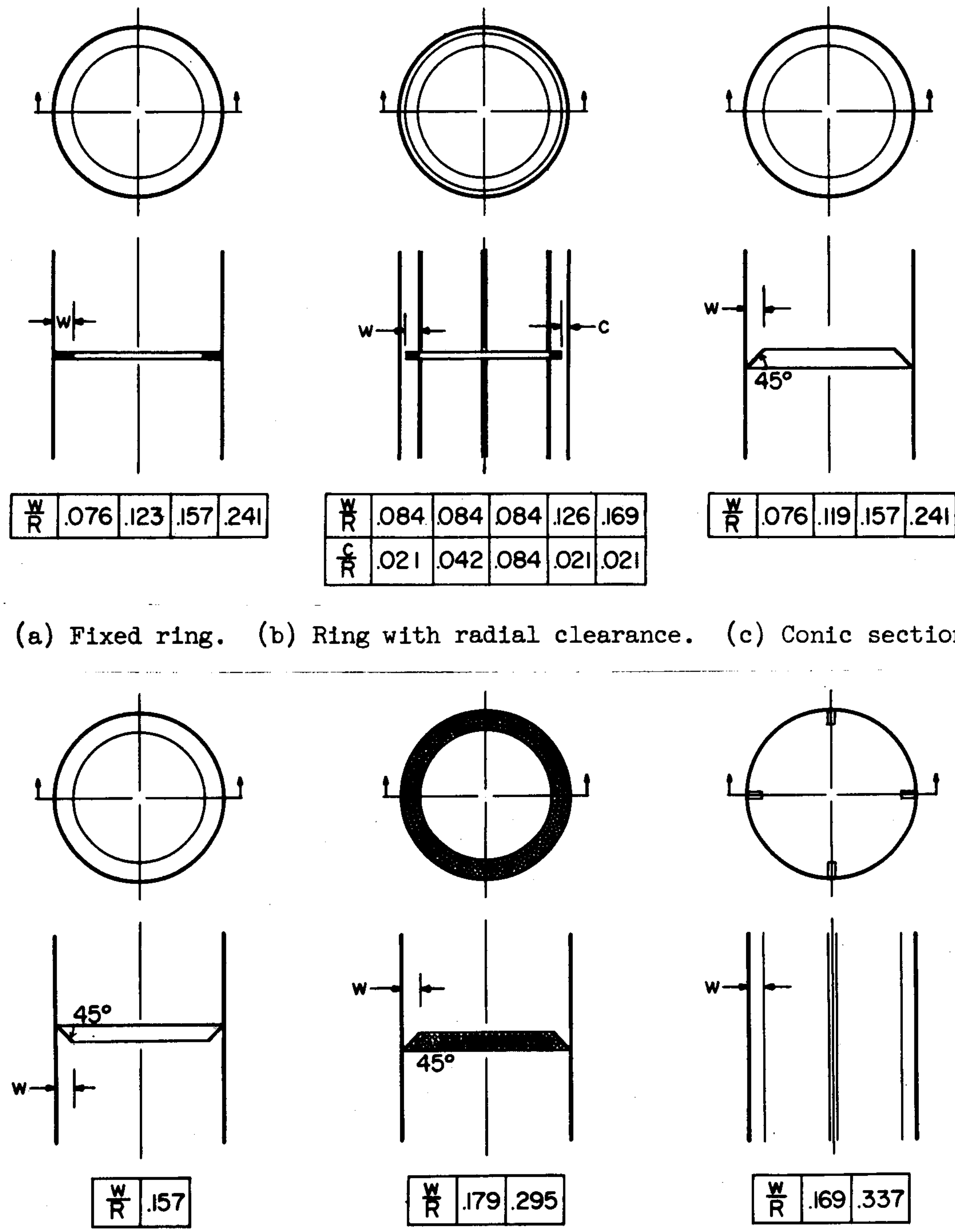

$\frac{w}{R}$	.076	.123	.157	.241

(a) Fixed ring.

$\frac{w}{R}$	.084	.084	.084	.126	.169
$\frac{c}{R}$	.021	.042	.084	.021	.021

(b) Ring with radial clearance.

$\frac{w}{R}$	.076	.119	.157	.241

(c) Conic section.

$\frac{w}{R}$	.157

(d) Inverted conic section.

$\frac{w}{R}$	.179	.295

(e) Perforated conic section.

$\frac{w}{R}$	.169	.337

(f) Cruciform.

Figure 2.- Baffle configurations.

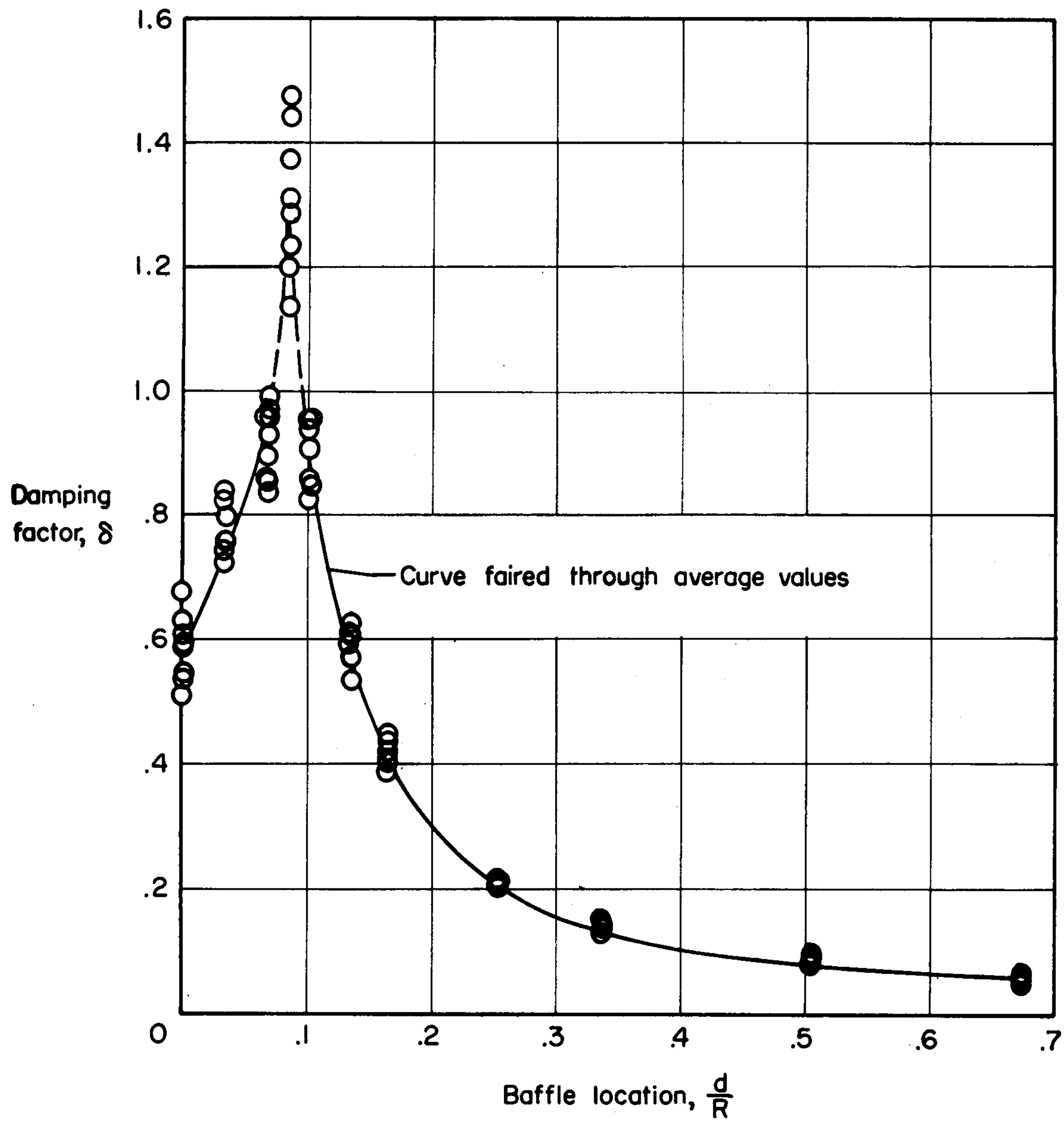

Figure 3.- A typical distribution of data for a fixed-ring baffle as a function of baffle depth. R = 6 inches; $\frac{h}{R}$ = 2.

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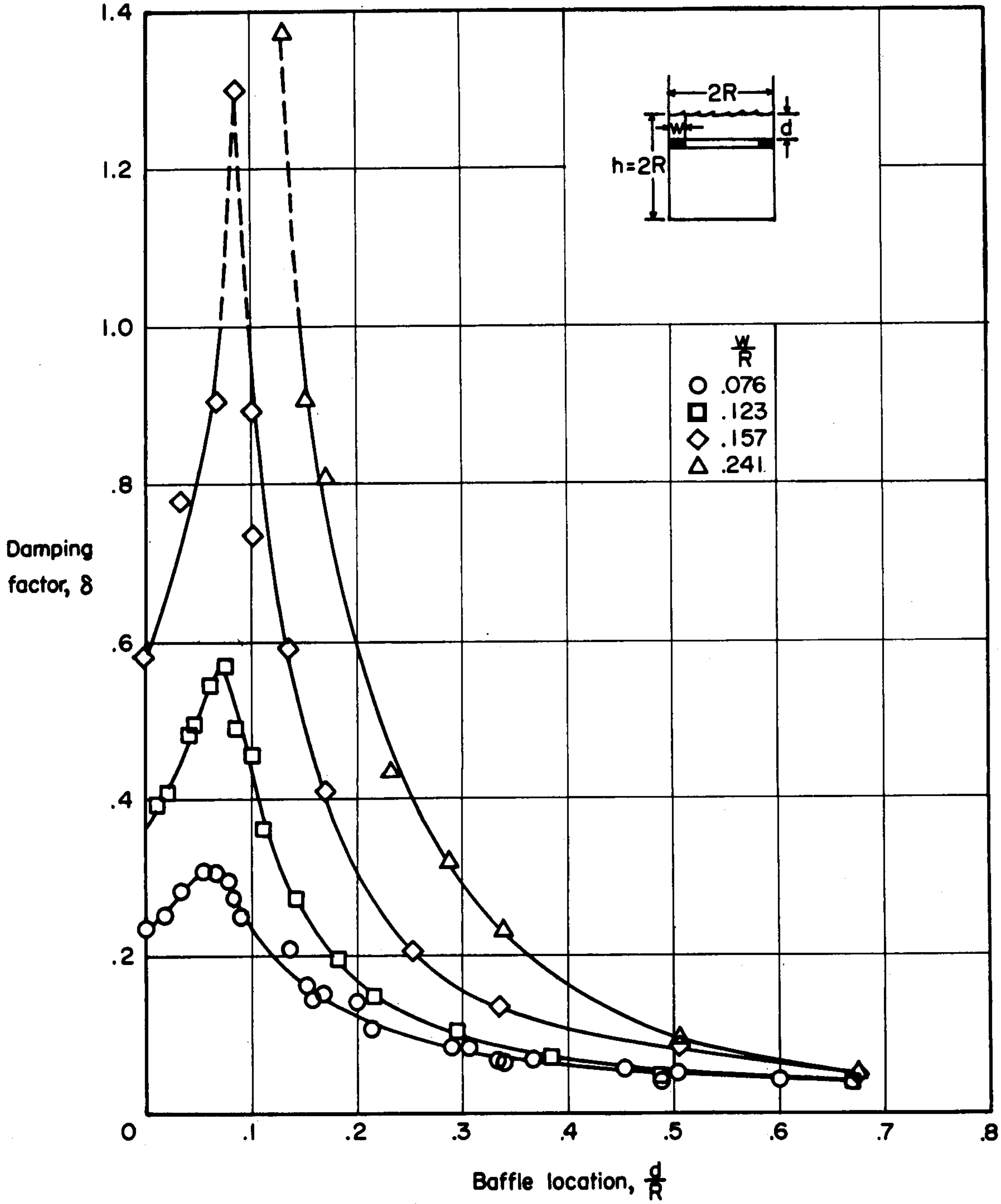

Figure 4.- Variation of damping factor with baffle location for fixed-ring baffle. R = 6 inches; $\frac{h}{R}$ = 2.

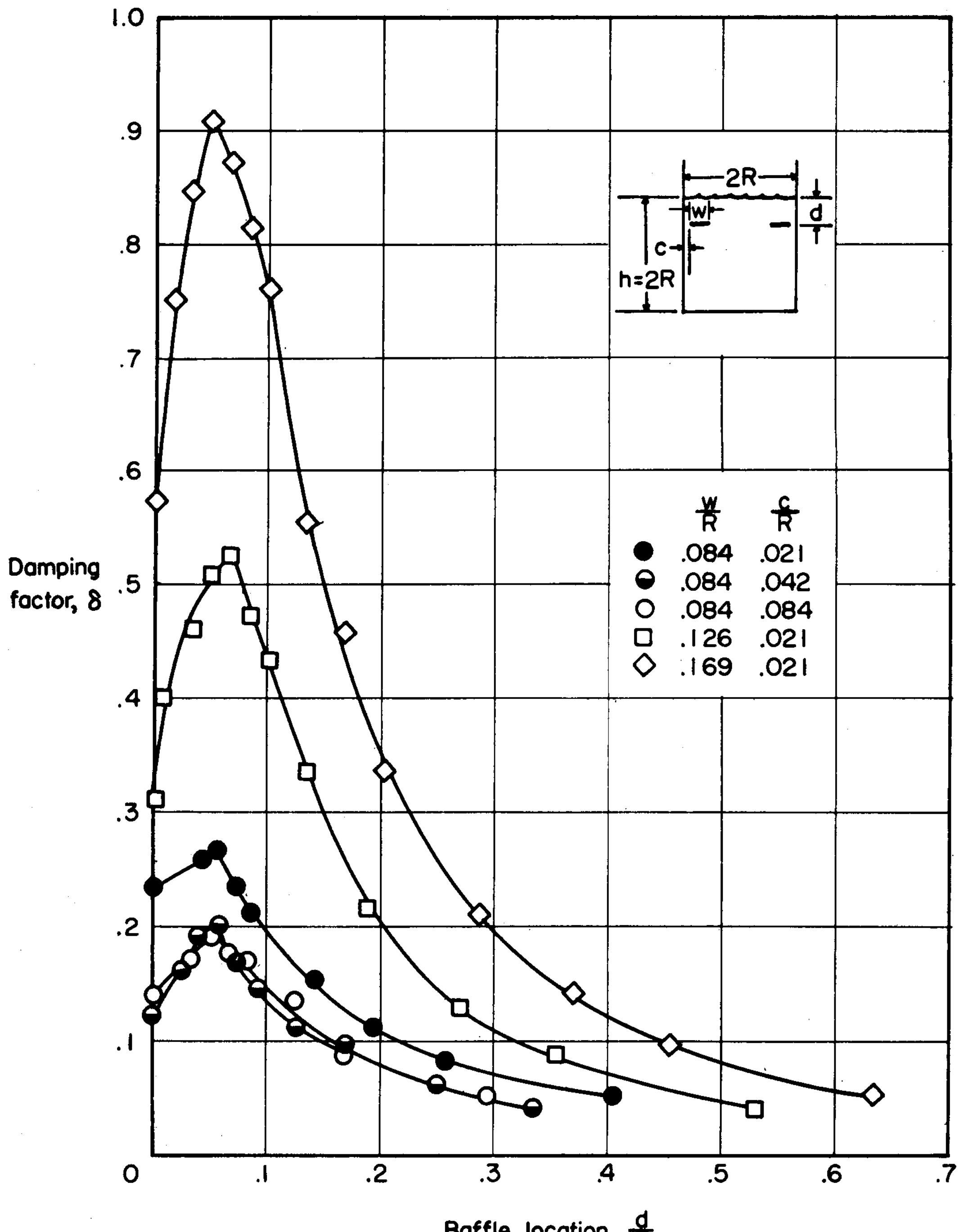

Figure 5.- Variation of damping factor with baffle location for ring-with-radial-clearance baffle. R = 6 inches; $\frac{h}{R} = 2$.

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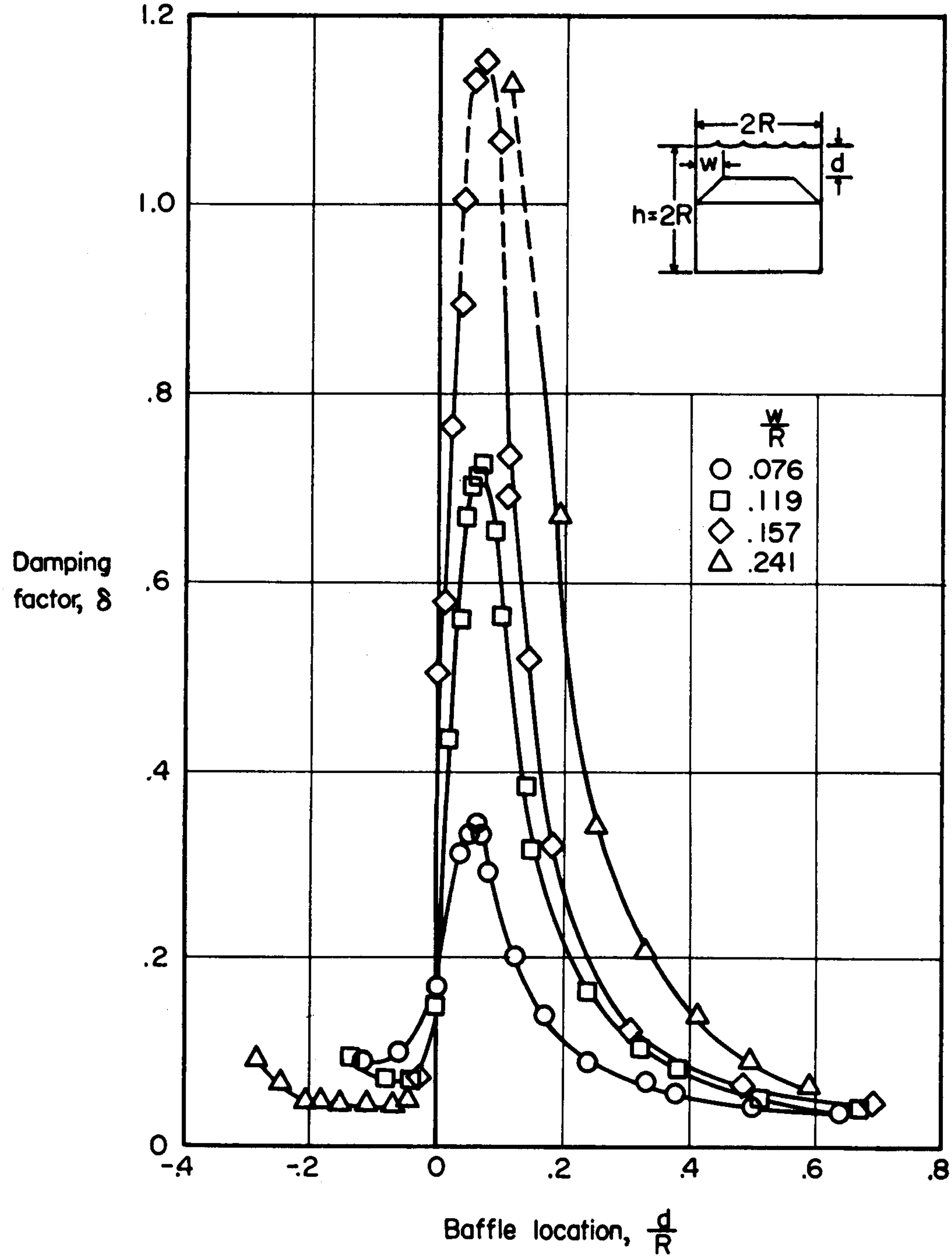

Figure 6.- Variation of damping factor with baffle location for conic-section baffle. R = 6 inches; $\frac{h}{R}$ = 2.

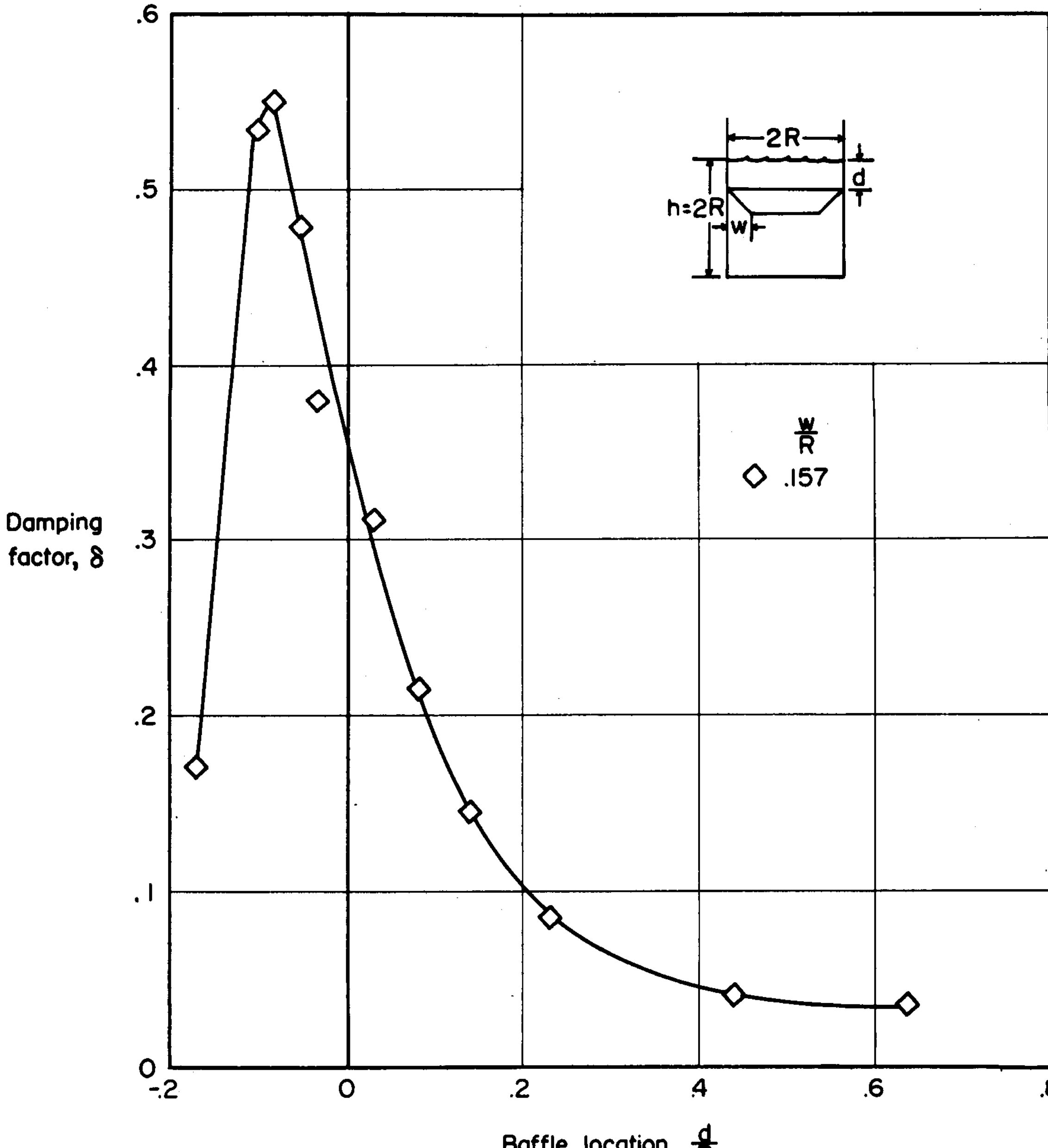

Figure 7.- Variation of damping factor with baffle location for inverted-conic-section baffle. R = 6 inches; $\frac{h}{R}$ = 2.

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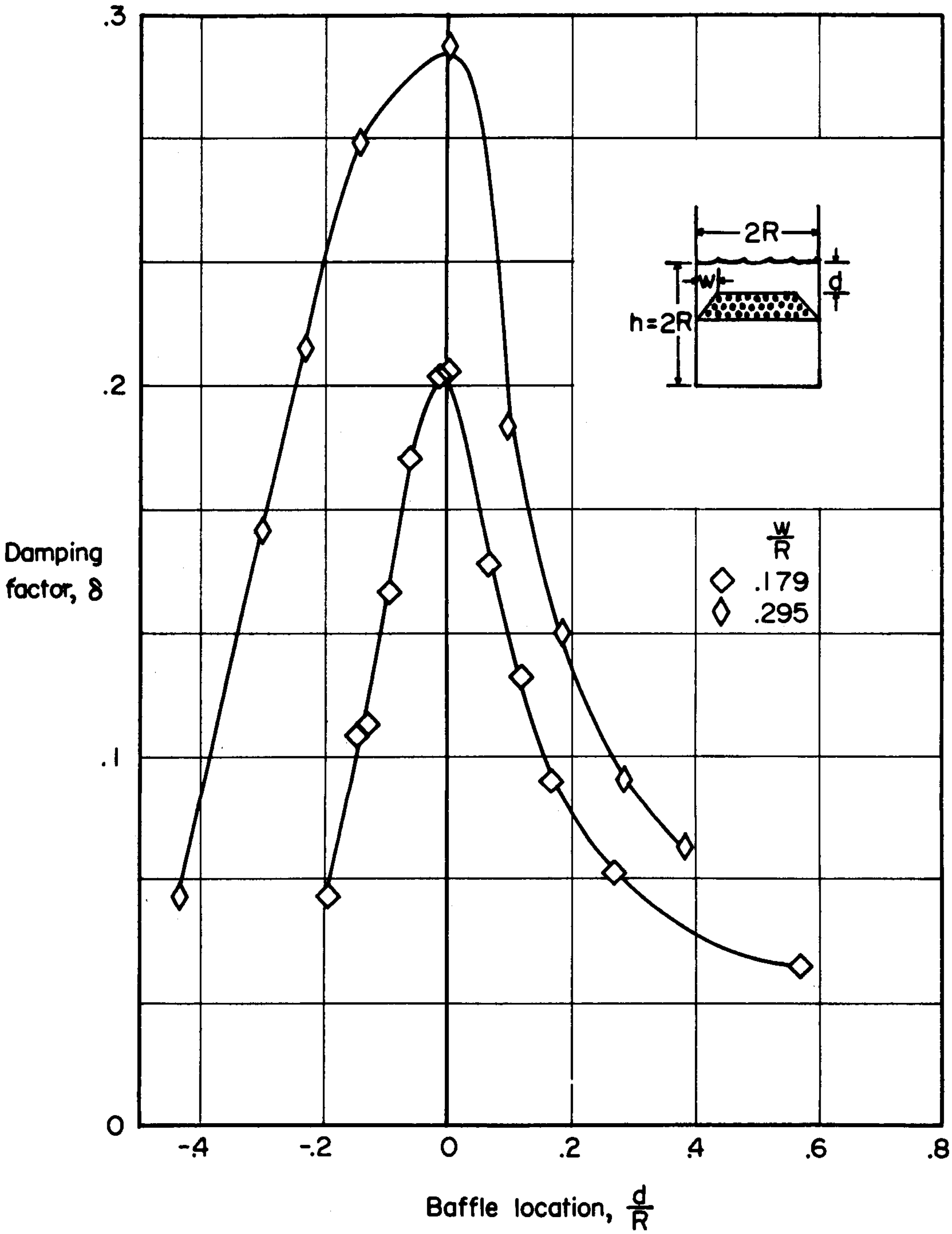

Figure 8.- Variation of damping factor with baffle location for perforated-conic-section baffle. R = 6 inches; $\frac{h}{R}$ = 2.

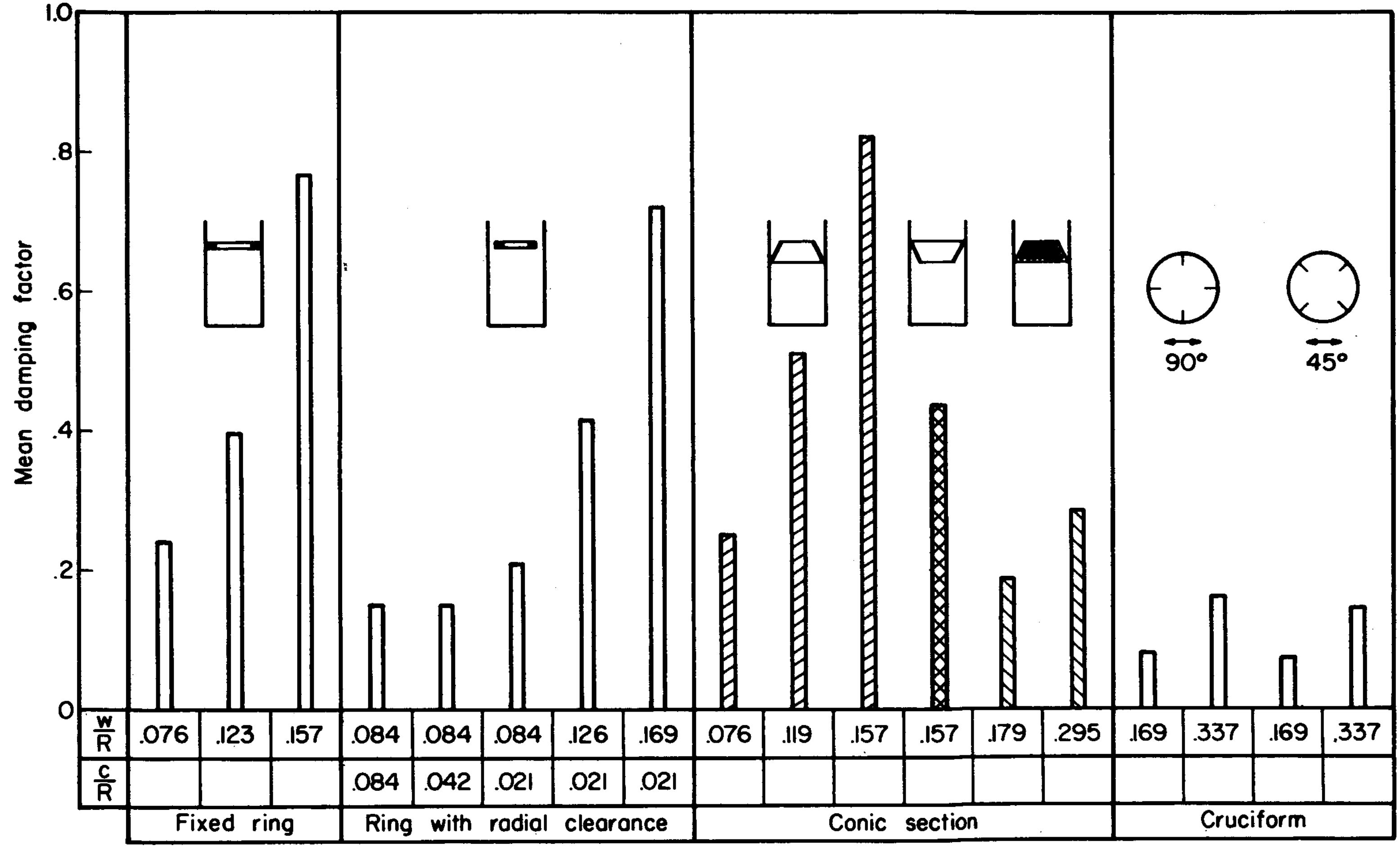

Figure 9.- Comparison of baffles.

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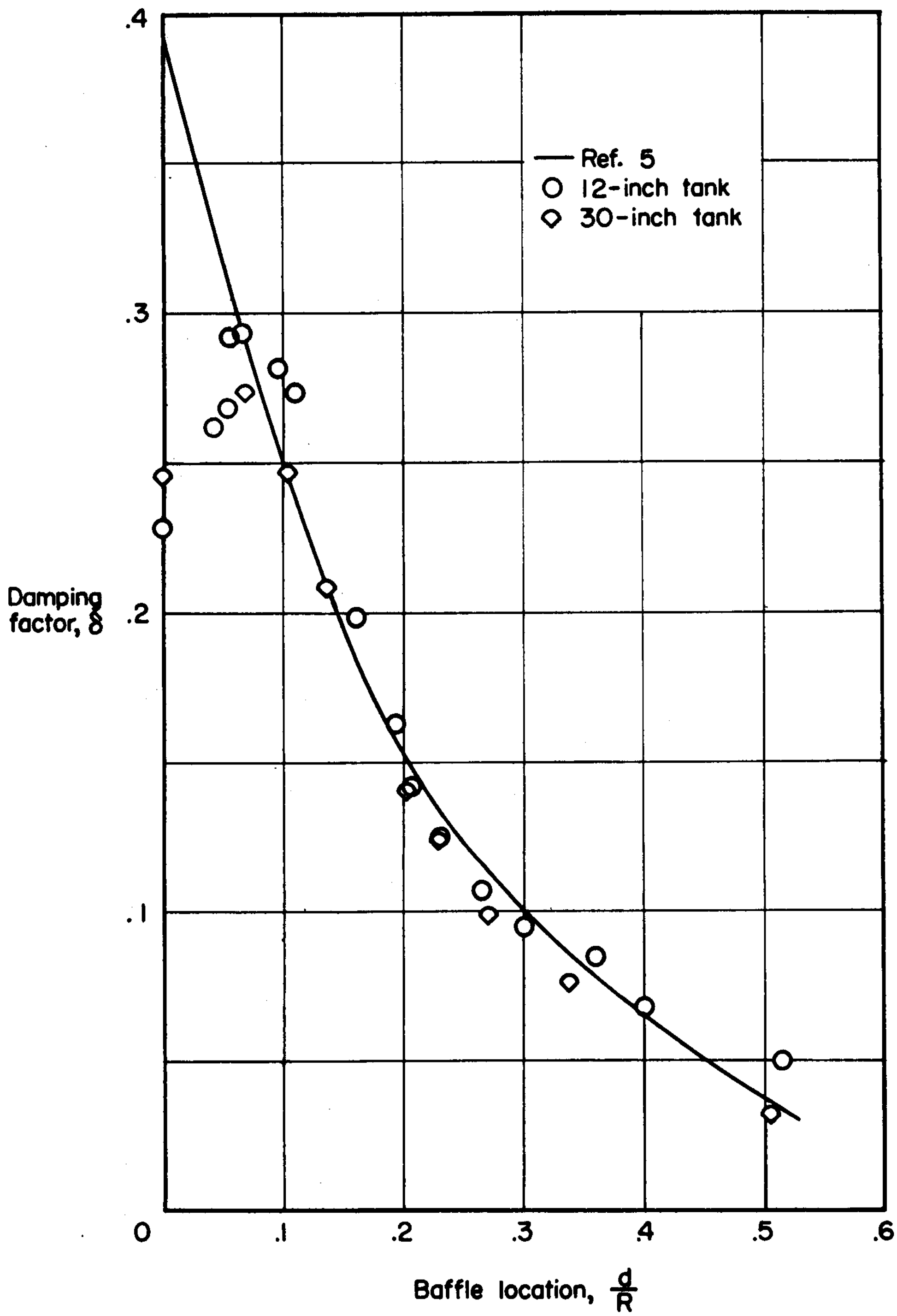

Figure 10.- Variation of damping factor with baffle location in the 12- and 30-inch-diameter tanks.

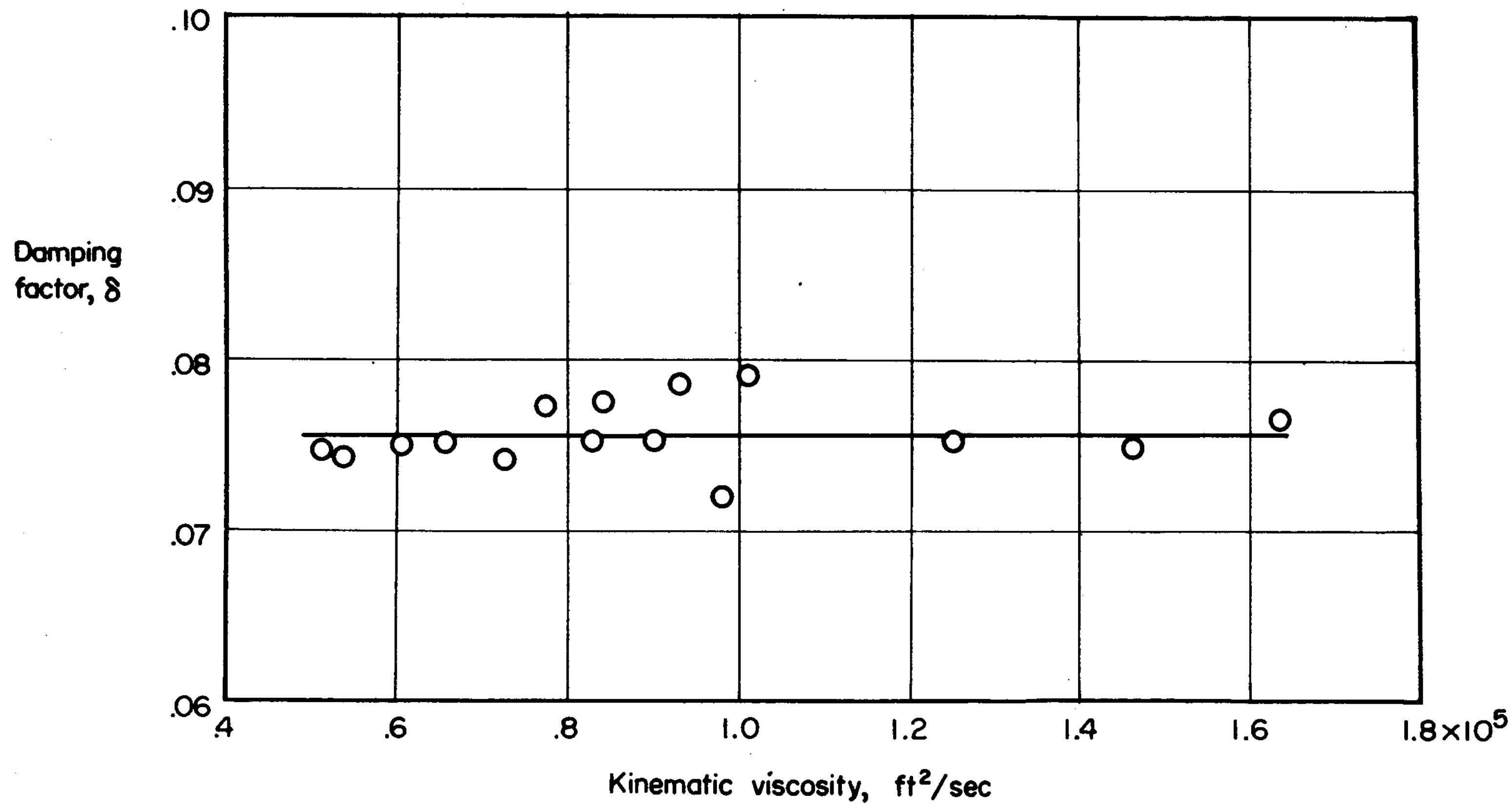

Figure 11.- Variation of damping factor with kinematic viscosity of water for fixed-ring baffle mounted in 30-inch-diameter tank. $\frac{W}{R} = 0.076$.

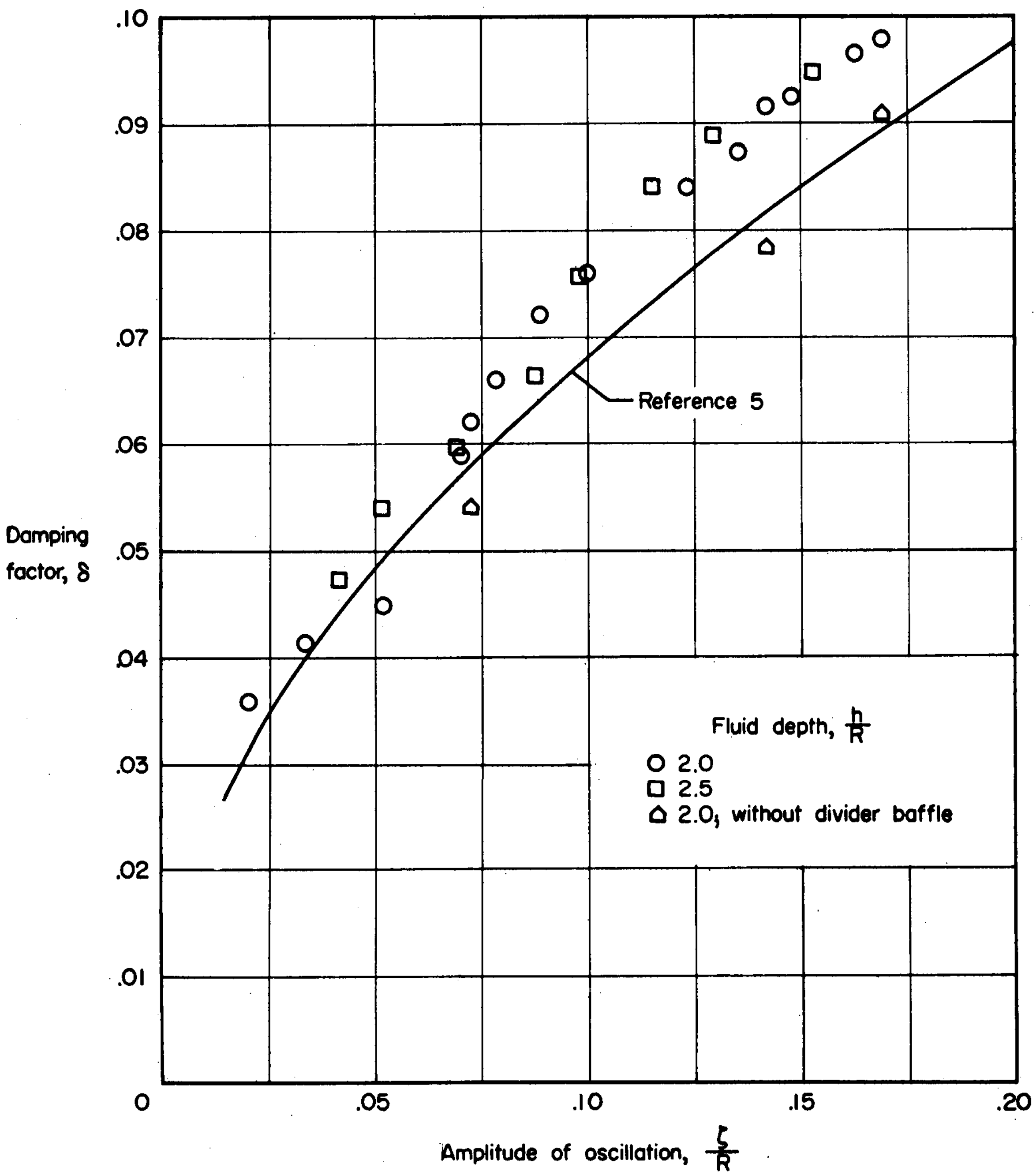

Figure 12.- Variation of damping factor with amplitude of oscillation for fixed-ring baffle. $\frac{W}{R} = 0.076$; $\frac{d}{R} = 0.333$.

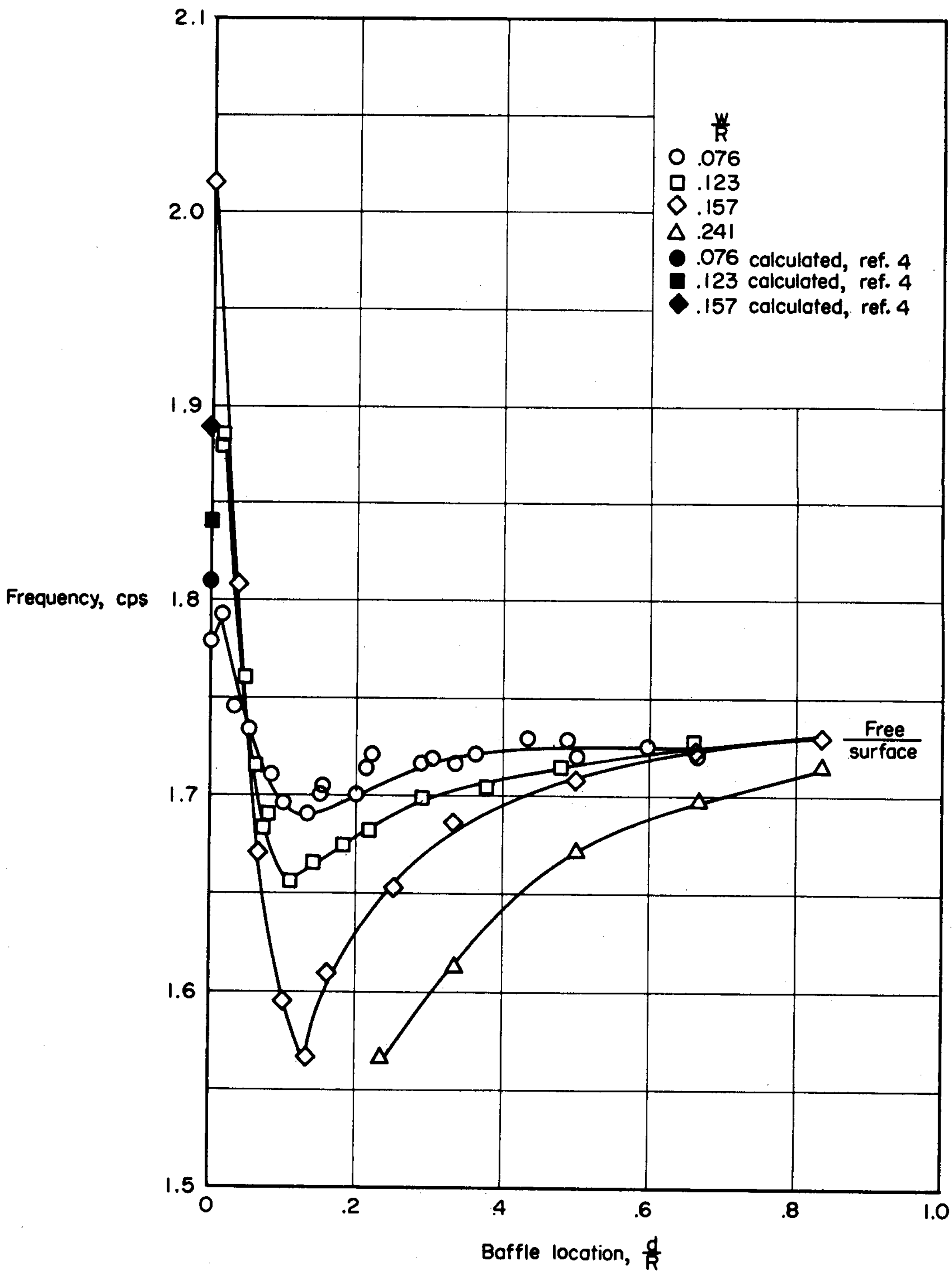

Figure 13.- Variation of frequency with baffle location for fixed-ring baffle.

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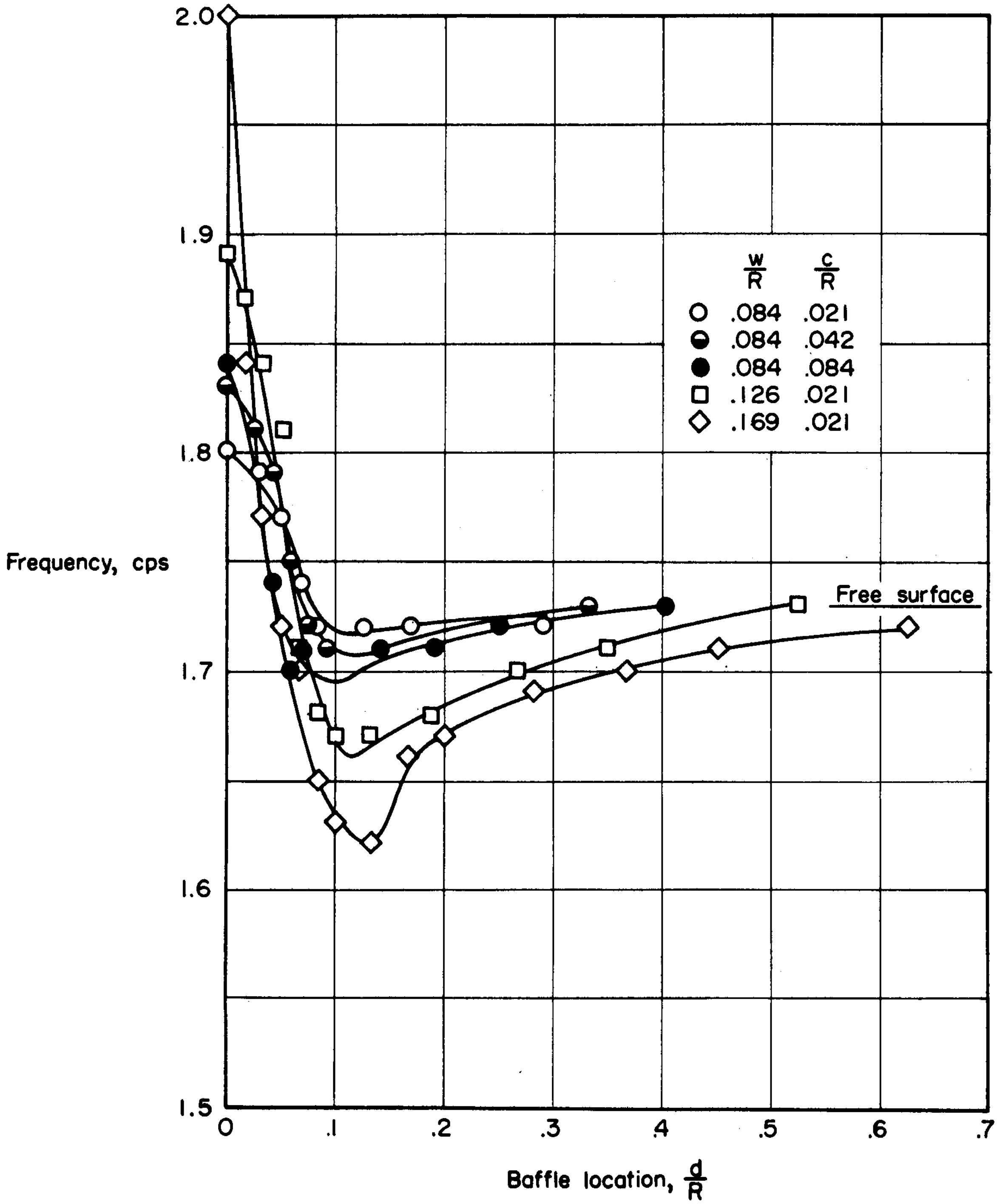

Figure 14.- Variation of frequency with baffle location for ring-with-radial-clearance baffle.

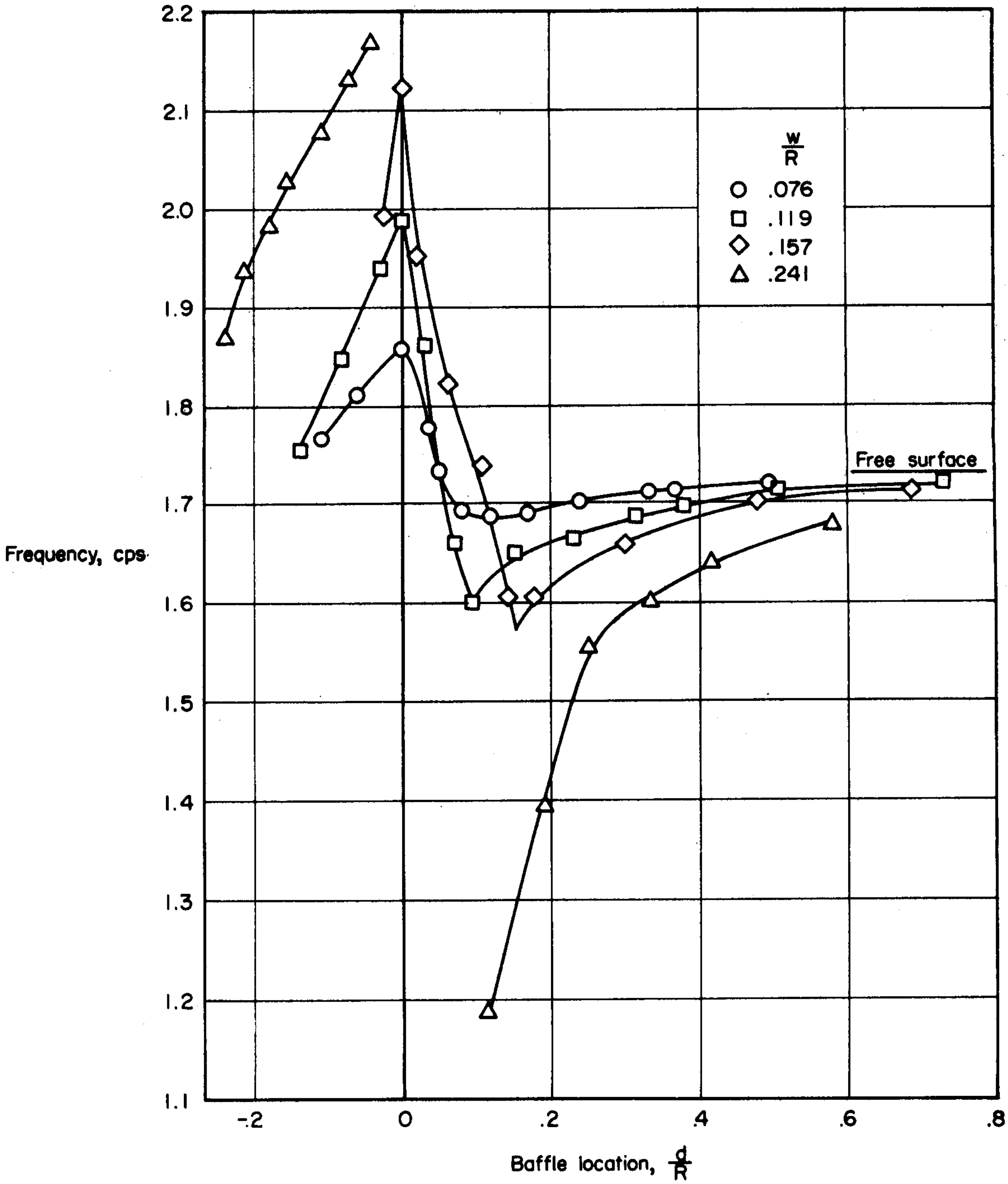

Figure 15.- Variation of frequency with baffle location for conic-section baffle.

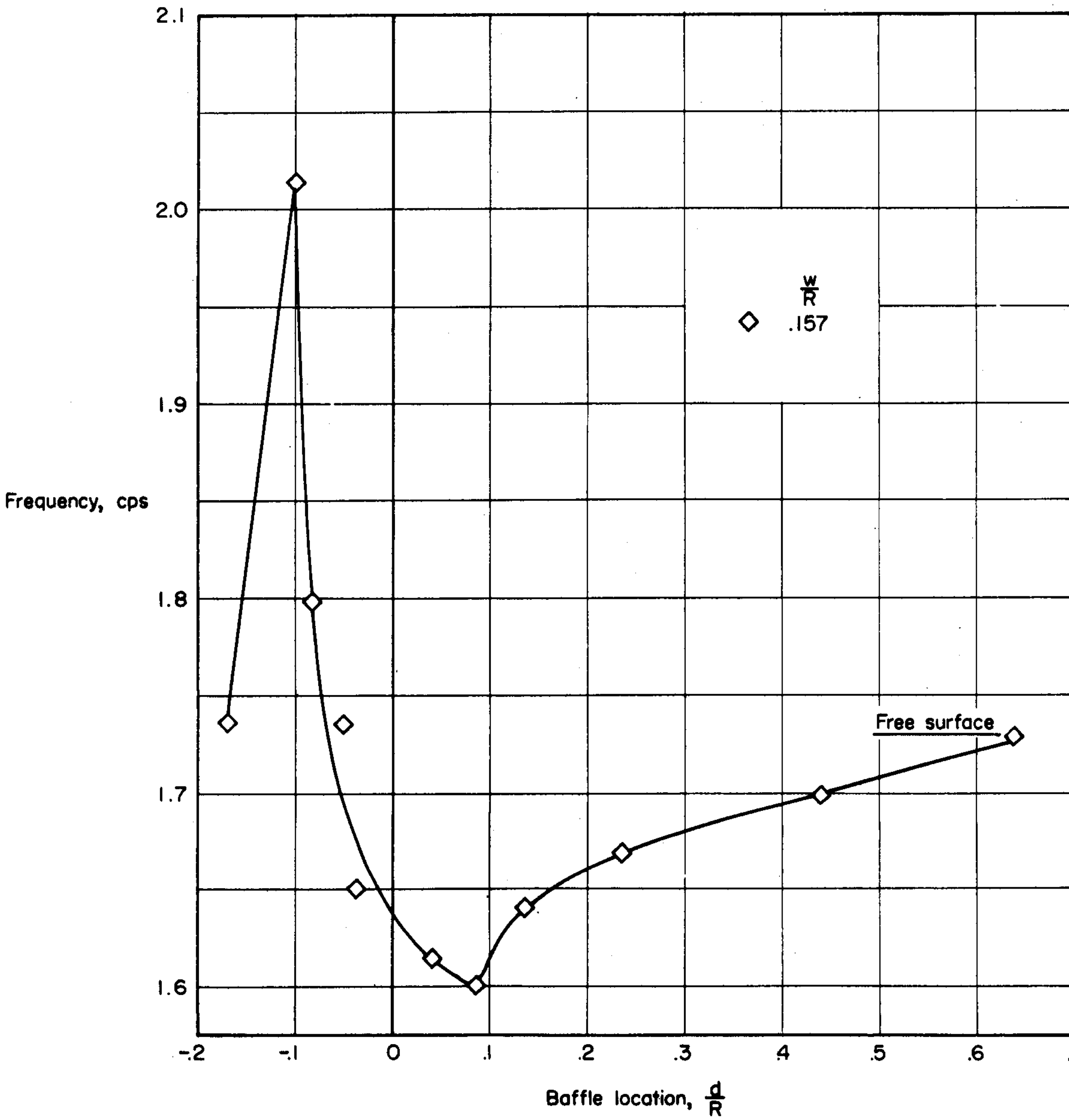

Figure 16.- Variation of frequency with baffle location for inverted-conic-section baffle.

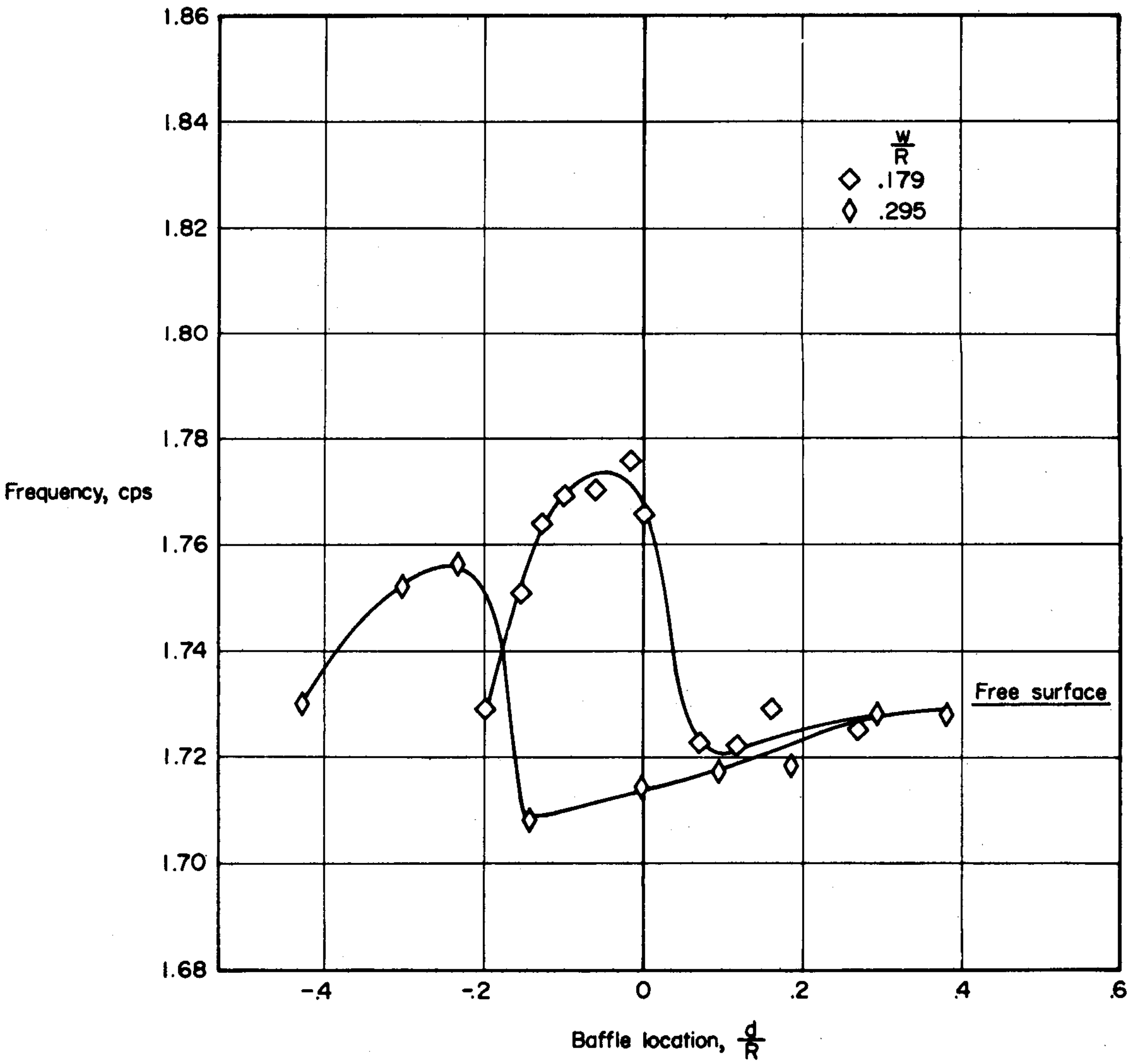

Figure 17.- Variation of frequency with baffle location for perforated-conic-section baffle.